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Plastic Pipe Alternatives Assessment

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Executive Summary

Plastic pipe is increasingly being used in place of traditional materials (copper, steel, concrete, vitrified clay) in a variety of applications. Lower material cost, ease of installation, resistance to chemicals, resilience and durability are key characteristics that have made plastic pipe popular. However, increasing concerns have been raised in recent years about the environmental profile of plastic pipe. Particular concern has been raised about the chemicals used in plastic pipe production and otherwise associated with the life cycle of these pipes. While sharing a common origin in fossil fuels, each of the different plastics used in pipes is manufactured through different procedures and contains different chemicals with unique environmental characteristics. This report was commissioned by the City of San Francisco to identify key attributes of the different plastic pipe types to assist the City in aligning its pipe purchasing policies with its chemical and other environmental concern policies.

This study seeks to answer the question of whether there are significant differences between the plastics used to manufacture pipes with a focus on priority environmental health impacts and end of life recyclability. No determination is made on whether plastics are either more or less preferable to the traditional materials used to manufacture pipes. Rather the evaluation is for decision-makers interested in understanding the environmental differences between plastics.

In this report, the plastics used to manufacture pipes are analyzed and compared for ***chemical hazards***, ***recyclability*** and ***performance***. The chemical hazard and recyclability assessments evaluate the environmental sustainability of plastics, while the performance assessment gauges the technical, market, and economic viability of the materials in different applications.

Five plastics commonly used in pipes are evaluated:

- Acrylonitrile butadiene styrene (ABS)
- High density polyethylene (HDPE)
- Cross-linked polyethylene (PEX)
- Polypropylene (PP)
- Polyvinyl chloride (PVC and CPVC[1])

The emphasis of the hazard assessment method used in this report is to **prevent pollution at the source by** avoiding materials and processes that use or generate priority hazardous chemicals. Rather than attempting to determine the quantity of all chemicals generated as pollution and minimizing the volume of those discharges, this hazard assessment method guides decision-makers to materials that are less hazardous across their life cycle by **prioritizing the avoidance of chemicals that are chronic human health hazards, persistent, or bioaccumulative.**

The ***chemical hazards*** examined when analyzing the life cycle of these materials include: carcinogenicity, mutagenicity, reproductive toxicity, endocrine disruption, persistence, and bioaccumulative capacity.[2] ***Priority Chemicals*** in this study are hazardous chemicals that have been targeted for reduction or elimination on a select set of US and international governmental lists.[3] In this analysis, therefore, a preferable plastic is one that does not use as input or generate as output a chemical on the referenced governmental chemical hazard lists and that is truly closed loop recyclable with a strong infrastructure to facilitate that recycling.

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[1] CPVC – chlorinated polyvinyl chloride. A modified form of polyvinyl chloride that has more chlorine atoms per repeating monomer unit than does the polyvinyl chloride molecule. This extra chlorine gives CPVC strength at higher temperatures than PVC.

[2] This report does not examine all the potential hazards – including ergonomics, flammability, corrosivity, and neurotoxicity – associated with a chemical.

[3] ***Priority Chemicals of Highest Concern*** for this study are those in the Stockholm Convention on Persistent Organic Pollutants, Priority Persistent Bioaccumulative Toxic (PBT) Pollutants and Priority Chemicals lists by the US Environmental Protection Agency (USEPA) and Chemicals for Priority Action by the Oslo-Paris Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR).

The analysis of the existing data leads to four primary conclusions:

- HDPE and PP are the most environmentally preferable plastics currently used to manufacture pipes under this chemical hazard and recyclability based analysis with no significant distinction between them. Yet even these plastics have their environmental downsides.
- HDPE, PP, and PEX create fewer chemical hazards of high concern across their life cycles than ABS and PVC.
- Plastic pipes are currently seldom recycled. Yet of the plastics used to manufacture pipes, a few general trends emerged. HDPE and PP are the most recyclable and recycled of the plastics (used in pipes). While ABS is recyclable, the recycling markets are small. PEX is inherently difficult to recycle. Finally, while PVC is recyclable under some circumstances, it is considered a contaminant in many recycling programs and its use is increasingly avoided in the automotive sector.
- Plastic pipe alternatives exist in the Prefer category in this analysis (HDPE and PP) that perform equal to or better than the plastics in the Avoid and Concern categories (PVC, ABS and PEX) for each of the pipe applications studied. Availability of preferable alternatives is good in North American markets with the exception of drain-waste-vent (DWV) applications The entry of new PP and HDPE products, with encouragement from forward looking environmentally preferable purchasing policies, is expected to expand availability of preferable alternative options in the North American market for all applications, including DWV.

All the plastic materials examined here have a common raw material origin in crude oil and natural gas. The extraction and refining of oil and gas generate Priority Chemical byproducts. All the plastics examined here, therefore, share a common set of chemical hazards from these processes.

PVC is slightly different than the other plastics because 57% of the weight of raw PVC resin (before additives) is from chlorine manufactured from brine (salt water) instead of from petrochemicals. Chlorine manufacture, however, also creates a similar set of Priority Chemical byproducts. Neither chlorine manufacturing nor oil and gas refining is a more environmentally preferable production system. Therefore the environmental differences between plastics emerge most significantly after the raw material extraction and refining stages. In this analysis, ABS and PVC stand out for their unique association with Priority Chemicals of Highest Concern throughout the rest of their life cycles.

PVC is the only plastic examined in this report to have persistent organic pollutants (POPs) targeted for elimination by the Stockholm Convention throughout its life cycle – that is, after the extraction and refining stages that all plastics share. Throughout the manufacture of PVC, dioxins, furans, hexachlorobenzene, and PCBs continue to be unavoidably produced, primarily because of its chlorine content.

Dioxins are further associated with the combustion of PVC products both during the use phase in accidental building and vehicle fires and at the end of life in incineration and landfill fires.

The unique toxicity of these chemicals, along with their persistent and bioaccumulative nature, has made them a top international priority for elimination[4] . PVC is also the only plastic examined here to have OSPAR Chemicals for Priority Action (organotins, lead, and possibly cadmium) in the final product itself.

Both ABS and PVC differ from the other plastics in their use of carcinogens[5], mutagens, reproductive/developmental toxicants, and endocrine disruptors, either as inputs into the manufacturing process and/or as inputs into the final product.[6]

Recyclability is evaluated primarily on indicators from current recycling markets and evaluations from parallel industries utilizing these plastics. Little recycling is being done with any plastic pipes. All of the plastics are theoretically recyclable and token plastic pipe recycling programs exist for each[7]. However there are significant moves away from PVC, because it is difficult to recycle, and toward the polyolefins

[4] Stockholm encourages product substitution as a method to eliminate these chemicals, reinforcing the importance of prevention through establishing preferences rather than through risk assessment based pollution management.
[5] All of the polymers do use one carcinogen - carbon black - for pipes that may be exposed to UV (ultraviolet) light.
[6] Note that the analysis is limited to the chemical class level for many of the additives used to manufacture plastic pipes as the specific chemical data is considered proprietary by manufacturers.
[7] Although for PEX the only known programs are waste to energy conversion, not true recycling.

(HDPE and PP), with ABS somewhere in the middle. The data indicate that the markets for recycling HDPE and PP will be more robust than PVC and PEX in the future with ABS less certain.

Performance is evaluated on installation, cost, availability and chemical resistance, durability, life span and other related issues. Use of PEX is restricted to relatively small diameter indoor water distribution applications and ABS is generally only used for DWV applications. PVC, PP and HDPE all perform satisfactorily in all applications. Availability is good for all types except for PP in North America.

Table 1 summarizes the results of the analysis and the conclusions of this report.

The hazard and recycling assessments clearly indicate that HDPE and PP are more environmentally preferable than PVC. ABS and PEX occupy a middle ground of concern between PVC at least preferable and HDPE / PP at most preferable. ABS is in the middle ground because of its better recycling profile than PVC. While PEX is preferable to ABS and PVC on chemical hazards, questions remain about its recyclability.

Performance characteristics are generally not an obstacle to using at least one of the polyolefins (HDPE, PP or PEX) to replace the PVC and ABS materials in each application and market availability is growing in all areas. DWV is the only area with market availability obstacles significant enough to slow down replacement at this time.

Table 1. Summary of Plastic Pipe Environmental Preferability Analysis

	[illegible]	Concern		Prefer		
	PVC	ABS	PEX	PP	HDPE	Preferable
Summary of chemical hazard & recyclability assessments	[illegible]	•more chemical hazard •low recycling	•less chemical hazard •very limited recyclability	•less chemical hazard •good recyclability	•less chemical hazard •good recyclability	Truly preferable plastic pipes do not yet exist
--- Chemical Hazard Assessment ---						
Stockholm POPs (outputs after refining)	[illegible]	+ none	+ none	+ none	+ none	
OSPAR & USEPA PBT & Priority Chemical (inputs)	[illegible]	+ none	+ none	+ none	+ none	
Chronic toxicants; Carcinogens, mutagens, developmental or reproductive toxicants or endocrine disruptor (inputs)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
Other PBT Outputs	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	
--- Recyclability Assessment ---						
Summary recycling markets and recyclability assessment	[illegible]	Recyclable but small markets	[illegible]	+ Established post consumer recycling markets (automotive)	+ Established post consumer recycling markets (bottles)	
--- Performance / Availability Assessment ---						
- Water distribution	Good/Good	Not used/NA	Good/Good*	Good/Poor*	Good/Good*	
- Drain/Waste/Vent	Good/Good	Good/Good	Not used/NA	Good/Poor	Not used/NA	
- Sanitary sewer	Good/Good	Not used/NA	Not used/NA	Good/Poor	Good/Good	
- Storm sewer	Good/Good	Not used/NA	Not used/NA	Good/None	Good/Good	
- Irrigation & drainage	Good/Good	Not used/NA	Not used/NA	Good/None	Good/Good	
- Irrigation & drainage	Good/Good	Not used/NA	Not used/NA	Good/Poor	Good/Good	

*PEX is used only in small diameter piping primarily for water distribution and radiant systems in buildings. HDPE for water distribution is used primarily in larger diameter piping outside the building. PP is just beginning to be marketed in North America

Introduction

Plastic pipe is increasingly being used in place of traditional materials (copper, steel, concrete, vitrified clay) in a variety of applications. Lower material cost, ease of installation, resistance to chemicals, resilience and durability are key characteristics that have made plastic pipe popular. However, increasing concerns have been raised in recent years about the environmental profile of plastic pipe. Particular concern has been raised about the chemicals used in plastic pipe production and otherwise associated with the life cycle of these pipes. While sharing a common origin in fossil fuels, each of the different plastic pipe polymers is manufactured through different procedures and contains different chemicals with unique environmental characteristics. This report was commissioned by the City of San Francisco to identify key attributes of the different plastic pipe polymers to assist the City in aligning its pipe purchasing policies with its chemical and other environmental concern policies.

This report surveys currently available data about chemicals associated with the life cycle of five major polymers commonly used in plastic pipes (ABS, HDPE, PEX, PP, and PVC). It assesses each polymer type by the characteristics of chemicals associated with it - such as persistence, bioaccumulation, carcinogenicity and reproductive toxicity - and whether any of those chemicals have been identified on a select set of national and international governmental lists as key chemicals of policy concern. The report also briefly looks at end of life options for recycling of the different pipe polymers. Then performance of each of the plastics pipe polymers is evaluated for a variety of primary uses.

The report concludes with recommendations for pipe polymers to avoid based upon particularly poor environmental profiles where alternatives exist that perform at least equally well.

Assessment protocol

The five plastic pipe polymers compared are:

- Acrylonitrile butadiene styrene (ABS)
- High density polyethylene (HDPE)
- Cross-linked polyethylene (PEX)
- Polypropylene (PP)
- Polyvinyl chloride (PVC, CPVC[8])

The applications assessed are:

- Water distribution
- Drain Waste and Vent (DWV)
- Sanitary Sewer
- Storm Sewer
- Irrigation and Drainage
- Duct and conduit

The analyses of hazards, recyclability, and performance are designed to assist the City in aligning its pipe purchasing policy with four key City values:

- **Reducing chemical hazards:** The City has taken a series of measures to reduce the toxic hazards associated with its operations in the City and in the larger environment beyond the City limits. Particularly relevant to this analysis is the City and County Commission on the Environment's Dioxin Resolution (No. 021-098-COE), which resolved to designate dioxin pollution as a high priority for elimination. This report identifies the key environmental health concerns associated with the chemicals used and released in the life cycle of each pipe material.
- **Precautionary principle:** The City of San Francisco has committed to identifying areas of its purchasing policy that impact issues where threats of serious or irreversible damage to people or natural systems exist. Plastic pipes have been identified as one of those areas due to the chemical releases associated with polymer manufacture, use and disposal. This report provides the careful analysis of alternative plastic pipes that the precautionary principle requires, using the

[8] The closely related chlorinated polyvinyl chloride or CPVC, used for higher temperature water delivery pipes, is considered a variant of PVC and not separately treated for this analysis.

best science available to help the City select materials that present the least potential threat to human health and natural systems across their life cycle[9].

- **Zero waste:** The assessment evaluates recyclability for each of the materials to help the City move toward its goal of realizing a zero waste materials stream.
- **High performance:** The assessment identifies relative performance issues for each plastic pipe polymer to assist the City in assuring that it uses materials that will perform well, be durable, cost effective and last in their application.

The final summary evaluation is a qualitative analysis based upon absolute screening criteria, not a quantitative impact analysis.

The resulting evaluation:

- **Characterizes chemical hazards** across the life cycle of pipes. The goal is to eliminate the use of plastics that contribute to key environmental health concerns. This is assessed by screening the life cycle of the target plastic polymers and their additives for the use or generation of chemicals listed in the Stockholm POPs and OSPAR agreements and identified on US EPA, California Proposition 65, and other key governmental lists. The plastics are then categorized into a hierarchy of concern based upon this hazard screening.
- **Characterizes recycling** options at the end of life, looking at both current recycling rates and potential recyclability, including compatibility with other recycling streams. The plastics are categorized for preferability in this area with the goal to maximize potential for reuse and recycling and minimize waste.
- **Creates a hierarchy** of plastic pipe types, bringing together the results of the screening criteria applied to these chemical hazard and recyclability profiles. Pipe types are clustered into Avoid, Concern and Prefer categories. In this analysis, the ideal preferable plastic is one that does not use as input or generate as output a chemical identified on the referenced governmental priority chemical lists and that is truly closed loop recyclable with a strong infrastructure to facilitate that recycling.
- **Summarizes** the applicable performance characteristics for each pipe type and addresses how they apply to different typical applications.
- **Assesses performance** in each pipe application category to determine if pipes made from polymers which rate better on the chemical hazard and recyclability screening can be substituted for the polymer types identified for avoidance.

Hazard Assessment

Introduction

The assessment focuses on the life cycles of the pipe products from organic chemical production to end-of-life disposal[10]. This is a qualitative life cycle hazard assessment[11] which identifies the use and generation of toxic, persistent, or bioaccumulative chemicals associated with each material. Because the purpose of this assessment is to be used as a guide for **preventive and precautionary action**, the assessment is based upon identifying the presence rather than volume of toxic, persistent, or bioaccumulative chemicals in the material's life cycle. The primacy of **pollution prevention** as the method for managing toxic chemicals was established by the Pollution Prevention Act of 1990:

> The Congress hereby declares it to be the national policy of the United States that pollution should be prevented or reduced at the source whenever feasible; pollution that cannot be prevented should be recycled in an environmentally safe manner, whenever feasible; pollution that cannot be prevented or recycled

[9] For more discussion of the precautionary principle, see Appendix 1

[10] The reasons for separate handling of the initial stages of raw materials extraction and processing are explained later in the text under *Inventorying Inputs and Outputs in the Life Cycles of the Plastics*.

[11] For further discussion of the difference between a life cycle hazard assessment and other forms of life cycle assessments (LCA) see Appendix 1

should be treated in an environmentally safe manner whenever feasible; and disposal or other release into the environment should be employed only as a last resort and should be conducted in an environmentally safe manner.

The emphasis of the analytic method used in this report is to **prevent pollution at the source**, avoiding materials and processes that use or generate the most hazardous chemicals. Rather than attempting to determine the quantity of all chemicals generated as pollution and minimizing the volume of those discharges through end-of-pipe treatment, **this assessment method guides decision-makers to deal with pollution problems through substitution with materials that use and generate as byproduct across their life cycle, chemicals that are less hazardous – prioritizing the avoidance of chronic human health toxicants, persistent chemicals, or bioaccumulative chemicals.**[12]

To achieve this goal we:

1. Inventory:
- *Inputs*: the chemicals that are used as feedstocks or intermediaries in production of each of the products and
- *Outputs*: those chemicals that are byproducts from the production, use, or disposal of the material.

2. Compare:
- chemical inputs and outputs against a set of Priority Chemicals of Highest Concern, primarily persistent bioaccumulative toxic (PBT) chemicals, targeted by national and international governmental agreements for elimination (see lists below) and
- chemical inputs against governmental chronic toxicant lists (carcinogens, mutagens, reproductive toxicants, and endocrine disruptors) and very persistent or very bioaccumulative chemicals.

3. Prioritize:
- Order plastic pipe materials on the basis of avoidance of key chemicals of concern from each list.

Priority Chemicals of Highest Concern

This assessment first identifies Priority Chemicals of Highest Concern based upon the following four lists of chemicals identified and prioritized for reduction by government bodies due their potential to damage human and environmental health:

- **Stockholm Convention on Persistent Organic Pollutants** (POPs)[13], which is a short list of very persistent, bioaccumulative, and toxic organic chemicals targeted for phase-out by international agreement. The U.S. Government has signed, but not ratified, the Stockholm Convention.
- **The US Environmental Protection Agency's Priority (EPA's) Persistent and Bioaccumulative Toxic (PBT) Chemicals**[14]. PBTs that have been identified by the EPA for national action plans.
- **Oslo-Paris Convention for the Protection of the Marine Environment of the North East Atlantic (OSPAR) List of Chemicals for Priority Action** [15] managed by the European Commission. Chemicals on the OSPAR list are of high concern for water toxicity.
- The **US EPA Priority Chemicals**[16] list targeted for reduction in products and wastes in its National Partnership for Environmental Priorities (NPEP).

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[12] For further discussion of the issues behind the choice of precaution, pollution prevention and hazard assessment versus risk assessment or life cycle assessment (LCA) see Appendix 1.
[13] The text of the Stockholm Convention can be found at: http://www.pops.int/documents/convtext/convtext_en.pdf
[14] The list of priority PBT chemicals for which the USEPA is developing national action plans can be found at: http://www.epa.gov/opptintr/pbt/
[15] The list of chemicals identified by the OSPAR Commission for priority action can be found at: http://www.ospar.org/eng/html/
[16] The USEPA NPEP list can be found at: http://www.epa.gov/epaoswer/hazwaste/minimize/chemlist.htm

The chemicals associated with each list are identified in Appendix 2.

Chronic Toxicants as well as Very Persistent & Very Bioaccumulative Chemicals

Chronic toxicants in this assessment refer to chemicals associated with long-term chronic health effects or effects at sub-acute exposures. This assessment is based upon chronic toxicants and very persistent and/or bioaccumulative chemicals listed on the following already scientifically established lists:

Carcinogens are any chemical listed as such by the:

- International Agency for Research on Cancer (IARC)[17]
- U.S. National Toxicology Program[18]
- European Union in Consolidated List Directive 76/769/EEC [19]
- California Office of Environmental Health Hazard Assessment (OEHHA) for Proposition 65[20]

Mutagens, which can cause inheritable genetic damage, are any chemical listed by the European Union as a Category 1 or 2 mutagen in EU Consolidated List Directive 76/769/EEC[21].

Reproductive or developmental toxicants are any chemical listed by the European Union as Category 1 or 2 reproductive toxicant in EU Consolidated List Directive 76/769/EEC or listed as a reproductive/developmental toxicant under California Proposition 65.

Endocrine disruptors are any chemical listed by the European Union as a Category 1 or 2 endocrine disruptor in EU Consolidated List Directive 76/769/EEC. To be a Category 1 endocrine disruptor the chemical must have at least one study providing evidence of endocrine disruption in an intact organism. Category 2 endocrine disruptors have the potential for endocrine disruption.

Very persistent or very bioaccumulative chemicals are those listed by the Swedish National Chemicals Inspectorate's (Keml)[22]. The European Union defines "very persistent chemicals" as chemicals that have a half-life of greater than 60 days in water, or greater than 180 days in marine or freshwater sediment, or greater than 180 days in soil.[23] The European Union defines "very bioaccumulative" chemicals to have a bioconcentration factor for aquatic organisms of greater than 5000.[24] The European persistence lists do not include metals that are by nature infinitely persistent.

Inventorying Inputs and Outputs in the Life Cycles of the Plastics

Inputs: Primary raw materials: All the materials assessed here share a common primary raw material resource base: they are manufactured, at least in large part, from fossil fuels. The primary chemicals used to produce ABS, HDPE, PEX, and PP are derived from natural gas and crude oil.[25] The primary chemicals used to manufacture PVC are derived from a combination of these same fossil fuels and chlorine gas manufactured from brine (salt water). Chlorine makes up 57% of PVC in its raw pellet state. Each of these plastics also generally contains a range of additives discussed in further detail below.

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[17] The list of IARC evaluations can be found at: http://www-cie.iarc.fr/monoeval/grlist.html
[18] The US National Toxicological Program's Report on Carcinogens can be found at: http://ntp-server.niehs.nih.gov
[19] The consolidated version of Annex I of Directive 76/769/EEC (currently in force) including a consolidated list of CMR substances can be found at: http://europa.eu.int/comm/enterprise/chemicals/legislation/markrestr/index.htm
[20] The list of chemicals as known to the State of California to cause cancer or reproductive toxicity by the California Office of Environmental Health Hazard Assessment (OEHHA) is listed at: http://www.oehha.ca.gov/prop65/prop65_list/Newlist.html
[21] There is no equivalent US list for mutagenicity, however mutagens may be searched at GENETOX & Chemical Carcinogenesis Research Information System, http://sis.nlm.nih.gov
[22] Swedish National Chemicals Inspectorate (Keml) webpage: http://prio.kemi.se.
[23] Swedish National Chemicals Inspectorate (Keml) webpage: http://prio.kemi.se. The International Joint Commission (IJC www.ijc.org) adopted an even more conservative definition of a "persistent toxic substance:" any toxic substance that bioaccumulates in the tissue of living organisms, or any toxic chemical that has a half-life greater than eight weeks (56 days) in any medium (water, air, sediment, soil, or living thing).
[24] Swedish National Chemicals Inspectorate (Keml) webpage: http://prio.kemi.se.
[25] Coal-based byproducts such as coke gases (gases produced when converting coal into coke) are another potential raw material source of feedstocks for plastics. However, in the U.S., natural gas and crude oil are the overwhelming source of raw materials for plastics' feedstocks, therefore coal processes are not included in this analysis.

Since ABS, HDPE, PEX, and PP share a common petrochemical resource base, material selection between them will have no effect on avoidance of chemicals from raw materials extraction and primary chemical production. PVC shares the same petrochemical resource base as ABS, HDPE, PEX, and PP. The difference with PVC arises due to its chlorine content - 57% of the weight of raw PVC (before additives) is from chlorine manufactured from brine (salt water) instead of from petrochemicals. Appendix 3 lists the Priority Chemical outputs from chlorine production, fossil fuel extraction and refining for comparison[26]. Chlorine production has POPs outputs that aren't associated with fossil fuels (PCBs and hexachlorobenzene) while fossil fuels have POPs outputs not associated with chlorine production (aldrin and DDT). Both also have outputs in the other categories of Priority Chemicals of High Concern (US EPA PBTs and OSPAR and EPA Priority Chemicals). Therefore, neither crude oil refining or chlorine production is environmentally superior; both have significant priority chemical hazards associated with their output byproducts. It should be noted that chlorine production has a very serious mercury problem associated with it[27] and that chlorine itself is a highly toxic material.

This comparative analysis therefore focuses on the life cycle concerns after the initial raw material processing stage; that is after the raw material extraction, crude oil refining, natural gas processing, and chlorine production.

The assessment begins with an inventory of the principal organic chemicals used in the manufacture of the five plastics. Table 2 lists those chemicals for each plastic.

Table 2. Principal Organic Feedstocks Used to Manufacture Primary Pipe Polymers

PVC	ABS	PEX	PP	HDPE
Ethylene	Ethylene	Ethylene	Propylene	Ethylene
Ethylene dichloride	Benzene			
Vinyl chloride monomer	Ethylbenzene			
	Styrene			
	Acrylonitrile			
	1,3-Butadiene			

Inputs: Additives: All petrochemical plastics require additives to either facilitate the manufacturing process or to impart specific properties to the final product. The types of additives commonly used in plastic pipes include: antioxidants, antistatic agents, lubricants, ultraviolet (UV) stabilizers, and heat stabilizers. The specific additives used in plastic products, including pipes, are proprietary data and can vary widely among manufacturers, hence complete information was not available for this analysis.[28] Generic formulations that listed specific chemicals were found only for PVC sewer pipes used in Europe (see Appendix 4).

While specific chemical formulations for the additives used in each plastic pipe polymer were not available for this analysis, substantial generic data on additive practices were collected and assessed.

This report:

- Identifies the types of additives used in the manufacture of the plastic pipes: for example, UV light stabilizer.[29]

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[26] There are no known Priority Chemical outputs from brine production but there is insufficient data available for conclusion in this analysis.

[27] Nine chlor-alkali plants producing chlorine for PVC manufacture use mercury cell technology. Serious discrepancies and purchases indicate that the plants were not able to account for 65 tons of mercury in 200, more than emitted by all coal fired power plants. U.S. Senate Committee on Environment and Public Works "Senators Call On EPA To Document The Fate Of 65 Tons Of Toxic Mercury" http://epw.senate.gov/pressitem.cfm?party=dem&id=221813

[28] For example, in the case of ABS polymers, "Different manufacturers produce and process ABS significantly differently. Therefore, the selection of stabilizers has to be checked carefully for each process and application." Zweifel, 2000 p.78

[29] Sources include: *Chemical Economics Handbook*, "Plastics Additives" section by Modler, et. al. (1997); and the *Plastics Additives Handbook*, edited by Hans Zweifel (2000).

- Identifies the classes of chemicals used within each additive category: for example, benzophenone light stabilizers for the additive UV light stabilizer.[30]
- Identifies specific chemicals used as additives for specific polymers. For example, the UV light stabilizer 4-dodecyloxy-2-hydroxybenzophenone has been used as an additive in the manufacture of all five plastics considered in this report (ABS, HDPE, PEX, PP, and rigid PVC).[31] However, no data were located specifying the types of products using 4-dodecyloxy-2-hydroxybenzophenone.

The types of additives used to manufacture pipe grade polymers include:

- Lubricants and UV light stabilizers in all five plastics.
- Antioxidants and antistatic agents in ABS, HDPE, PEX, and PP.
- Stabilizers in PVC.

Carbon black is a common UV light stabilizer used in the manufacture of plastic pipes.

See Appendix 5 for a complete listing of classes and where they are used.

Note that the analysis is limited in scope on the specific additives used to manufacture each type of plastic pipe as this data is considered proprietary by manufacturers. To fully assess the relative toxicity of the polymers the City of San Francisco could collect data on the specific additives used in the manufacture of pipes. Due to the proprietary nature of this information, it is likely that the City of San Francisco would need to sign non-disclosure agreements or use an independent third party vehicle to gather and evaluate the data without making it subject to public disclosure.

Outputs: The toxic outputs - the releases of pollutants to air and water - are then inventoried for each stage of production of the principal feedstocks as well as for polymerization and compounding of the plastics. To inventory the full scope of pollutants generated and released during production, even those chemicals released in small quantities,[32] this inventory uses the raw data tables in the life cycle assessment study completed by Tellus Institute.[33] The data tables in the Tellus study are quite useful in identifying pollutants that are present in the wastewater and air emissions from manufacturing processes, but that do not appear in the US EPA's Toxic Release Inventory (TRI) due to falling under the TRI's emissions reporting threshold of 10,000 pounds.

Note that in this assessment all inputs into manufacturing-- both principal feedstocks and known additives (or additive classes where the exact additives are not known) -- are included. For outputs, however, only the pollutants from principal feedstocks are identified and assessed. The pollutant outputs from the production of additives have not been identified nor assessed.

Transportation: Inputs and outputs to transportation of pipes and their feedstocks are not included in the scope of this assessment. It is assumed that selection of plastic type will not consistently or inherently affect the type of transportation modes or fuel types. Therefore the chemical hazard of transportation inputs and outputs will not be affected by plastic type selection.

Installation: Chemicals associated with the pipe installation process are also not formally included in this assessment. It should be noted, however, that PVC and ABS use solvent based systems with known chronic toxicants[34], whereas the polyolefins exclusively utilize mechanical or thermal joining methods with no direct chemical inputs. This is not expected to change the rankings as it parallels the hazards identified elsewhere in the life cycle.

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[30] Ibid.

[31] Radian Corporation, 1987. Radian Corporation. 1987. *Chemical Additives for the Plastics Industry: Properties, Applications, Toxicologies*. Park Ridge, NJ: Noyes Data Corporation.

[32] For example, below Toxics Release Inventory reporting thresholds.

[33] Tellus, 1992. While the data in the Tellus Institute report is from the 1980s, it represents the most comprehensive, publicly available database that includes the soup of pollutants released from these processes at very low levels.

[34] Common elements of PVC pipe cement include tetrahydrofuran (suspected endocrine and developmental toxicant with inadequate carcinogenicity data to classify), methyl ethyl ketone (another (suspected endocrine and developmental toxicant), and cyclohexanone (another (also a suspected developmental toxicant) and PVC resin. ABS cement typically consists of methyl ethyl ketone and ABS resin

Hazards Assessment of the Chemicals

Priority Chemicals of Highest Concern: The assessment compares the inventory of chemical inputs and outputs against the Chemicals of Highest Concern (Stockholm POPs, EPA PBTs, and EPA/OSPAR Priority Chemicals). For the five plastic polymer life cycles, these chemicals are primarily found as pollutant outputs: the pollution from manufacture, use and disposal.

Appendix 3 details where in the life cycle of the five plastics these Chemicals of Highest Concern to governments are created as pollutant outputs.

The results of this analysis are as follows:

- **Inputs**: Only PVC uses Chemicals of Highest Concern in manufacturing– the additives organotins, lead, and cadmium, which are OSPAR Chemicals for Priority Action.
- **Outputs (byproducts)**: All of the plastics have both US EPA Priority PBT pollutants and OSPAR Chemicals for Priority Action associated with their life cycle: in the wastewater effluent from the manufacture of petrochemical feedstocks.

  PVC pipes are alone, however, in having Stockholm Convention POPs (dioxins, furans, PCBs, and hexachlorobenzene), as outputs in their life cycle beyond the initial raw material processing stage.

Chronic Toxicants, Persistent Chemicals, or Bioaccumulative Chemicals: The assessment then compares the inventory of chemical inputs to specific chemical hazards -- persistence, bioaccumulative capacity, and chronic toxicity -- for the primary organic chemical feedstocks and additives.

Appendix 6 details the toxicity of known inputs into each of the plastics.

The results include:

- All of the plastic pipes use a carcinogen (carbon black) for applications where the pipe may be exposed to UV light.
- Otherwise, ABS and PVC alone use:
  - carcinogens,
  - mutagens,
  - reproductive/ developmental toxicants, and
  - endocrine disruptors

  as either inputs into the manufacturing process and/or as inputs into the final product, even for non-UV protected product.

Note that unlike with PVC, where there are classes of chemicals used as stabilizers that are clearly hazardous (e.g., cadmium compounds, lead compounds and organotins), there are no such clearly hazardous classes of chemical additives used in ABS, HDPE, PEX, and PP pipes. For example, ABS, HDPE, PEX, and PP all use phenolic-based antioxidants. Unlike the lead compounds used in PVC pipes, hazards have not been identified for phenolic-based chemicals as a class. There is a phenolic-based antioxidant that is known to be an endocrine disruptor, bisphenol A. However, the only evidence found on the use of bisphenol A as an antioxidant states that it is used in PVC production[35].

This study evaluates the plastic manufacturing process inputs against the listings for both
A) the identified Chemicals of Highest Concern and
B) persistence, bioaccumulative capacity, and chronic toxicity.

The outputs, however, are only compared for Chemicals of Highest Concern. Since all of the plastics examined in this report have pollutant outputs that include a large number of additional chemicals that are persistent, bioaccumulative, or toxic, further evaluation from a chemical hazard screening perspective did not reveal any significant differences among the plastics.

[35] Noyes, 1987 note there is also some evidence that bisphenol A may also be used as a flame retardant in ABS, although it is unknown if this occurs in pipes.

Summary and Findings of the Hazards Assessment

Table 3 summarizes the data collected concerning the life cycle hazards to human and environmental health associated with the five plastics commonly used in pipes: ABS, HDPE, PEX, PP, and PVC.

None of the plastics can be characterized as completely environmentally sound from this hazards assessment:

- **Inputs**: All of the plastics -- **ABS, HDPE, PEX, PP, and PVC** -- use the **carcinogen carbon black** for pipes that may be exposed to UV light
- **Outputs**: All the plastic piping materials examined here -- **ABS, HDPE, PEX, PP, and PVC** -- have both **US EPA Priority PBTs and OSPAR Chemicals for Priority Action** pollutant outputs associated with their life cycle: these occur in the wastewater effluent from the manufacture the petrochemical feedstocks used to make the plastics. All of the plastics also have a significant number of other listed persistent bioaccumulative or toxic outputs.

ABS and PVC, however, stand out for their hazards due to their unique association with key chemicals of concern in their life cycles:

- **Inputs: ABS and PVC** alone use **carcinogens**[36], **mutagens, reproductive/developmental toxicants, and endocrine disruptors** either as inputs into the manufacturing process and/or as inputs into the final product, even for non UV protected product. **PVC** is the only plastic examined here to use **OSPAR Chemicals for Priority Action** in the final product itself.
- **Outputs: PVC pipes** are the only plastic pipe to have **Stockholm Convention POPs** (dioxins, furans, hexachlorobenzene and PCBs) associated with their life cycle after petroleum refining.[37]

ABS and PVC are considered environmentally less preferable in this analysis than HDPE, PEX, and PP because of their use of chronic toxicants as inputs in production that the other plastics avoid altogether. **PVC is judged less preferable than ABS** due to its unique association with outputs on the highest priority list (Stockholm POPs) throughout its life cycle (in the manufacture of its feedstocks and associated with the incineration of PVC products and accidental building fires) and for its use of US EPA and OSPAR Priority Chemicals as inputs. There is no differentiation between the other three plastics in this analysis. Table 3 summarizes the hazard assessment.

[36] As noted above the other plastics do use one carcinogen – carbon black – for UV protected pipe.
[37] Note that this analysis did not include transportation impacts as described above.

Table 3. Plastic Pipe Hazard Assessment – Chemicals of Highest Concern					
	Avoid	High Concern	Moderate Concern		
	PVC	**ABS**	**PEX**	**PP**	**HDPE**
Summary chemical hazard assessment	·EPA PBT & ·EPA/OSPAR Priority outputs plus ·Stockholm POPs outputs & EPA/OSPAR Priority inputs [illegible]	·EPA PBT & ·EPA/OSPAR Priority outputs plus additional ·Chronic toxicant inputs	·Significant EPA PBT & EPA/OSPAR Priority outputs	·Significant EPA PBT & EPA/OSPAR Priority outputs	·Significant EPA PBT & EPA/OSPAR Priority outputs
Chemicals Of Highest Concern On Regulatory Target Lists – Process Inputs					
Stockholm POPs					
US EPA PBT					
US EPA Priority Chemical	Cadmium, Lead				
OSPAR	Cadmium, Lead Organotins,				
Chemicals Of Highest Concern On Regulatory Target Lists – Pollution Outputs (post initial raw material processing)					
Stockholm POPs	Dioxins, Furans, PCB Hexachlorobenzene,				
US EPA PBT	Dioxins, Furans, Benzo(a)pyrene, Hexachlorobenzene, Hg, PCB, OCS	Benzo(a)pyrene, Hg, Lead	Benzo(a)pyrene, Hg	Benzo(a)pyrene, Hg	Benzo(a)pyrene, Hg
US EPA Priority Chemical	Cd, Dioxins, Furans, Hexachlorobenzene, PAHs, PCB, PCP	Cd, PAHs	Cd, PAHs	Cd, PAHs	Cd, PAHs
OSPAR	Cd, Dioxins, DEHP, Furans, PCB,PCP,PAHs	Cd, DEHP, PAHs	Cd, DEHP, PAHs	Cd, DEHP, PAHs	Cd, DEHP, PAHs
Chronic Toxicants, Very Persistent, or Very Bioaccumulative – Process Inputs					
Carcinogens	Cd, Carbon black, EDC, Lead compounds, VCM	1,3-Butadiene, Acrylonitrile, Benzene, Carbon black, Ethylbenzene, Styrene	Carbon black	Carbon black	Carbon black
Mutagens	Cadmium	1,3-Butadiene			
Reproductive / developmental toxicants	Cadmium, Lead compounds	1,3-Butadiene, Benzene			
Endocrine disruptors	Organotins	Styrene			
Very persistent chemicals					
Very bio-accumulative chemicals					

Recyclability Assessment

The ideal end of life options for a product allow it to be: a) reused as the same product (e.g., reusable glass or plastic bottles), b) recycled back into the same product, "closed loop recycling" (e.g., aluminum cans), or c) biodegraded into healthy nutrients for the soil (e.g., organic food). Less preferable than these options – although more preferable than landfilling or incineration – is the recycling of a product into a lower value product (e.g., office paper into cardboard boxes): this is called "downcycling." The dominant end of life option for plastic pipes, however, is disposal in either a landfill or incinerator.

This evaluation of the end of life potential for the different plastic pipes is based upon two characteristics:

- current recycling rates and practices, including downcycling, and
- potential recyclability, including integration into a cross industry commodity plan

SF recycling: The current reality of plastic pipe recycling is that the recycling of these products is marginal: very few plastic pipes are recycled in the U.S and most of them are downcycled. In San Francisco, as with most municipalities, plastic pipe is not accepted in residential curbside recycling programs or at drop off centers. Additionally, a survey of firms that recycle construction waste in the Bay Area revealed that most do not accept plastics of any type. Of the firms that do accept plastic building materials, the vast majority only accept HDPE or PP. A smaller number accept ABS, very few accept PVC and none are known to accept PEX[38]. See Table 5 for count of firms in the Bay area that accept the different plastics.

Most efforts to recycle plastic building materials have been thwarted by the daunting problem of creating a secondary material with market value. Establishing an infrastructure to gather, sort, and create a homogenous secondary plastic stream from building materials typically results in a material that costs more than virgin plastic and meets lower performance specifications.

Cross industry efforts: Office furniture maker Herman Miller is exploring solutions to the problem of material recycling in general and plastics recycling in particular by engaging other industry sectors in closing the recycling loop. One concept under exploration is to establish consistent plastic specifications and product labeling, in order to establish a broader commodity market for recycled plastics that could be utilized by manufacturers in different industry sectors. This requires a reversal away from the trend of the last several decades to more designer plastics that are custom tailored to each narrow application. Instead it favors standardization of plastic formulas for use in the widest range of applications[39].

To further understand the potential recyclability of the different pipe plastics and how they are positioned for this type of cross industry commodity recycling effort, the current practices in two other sectors where significant recycling is underway - bottles and automotive part - are assessed.

Bottle recycling: Bottle recycling drives the recycling rates of plastics in the U.S. A recent assessment of the state of plastics bottle recycling by the state of California found that:[40]

- plastics recycling rates continue to lag behind other materials like steel, aluminum, glass, and paper (p.1)
- plastics recycling is largely uneconomical without subsidies (p.1)
- the most recycled plastics nation-wide are PET and HDPE, which account for "more than one-half of national plastics recycling" (p.8)
- other plastics "recycled in significant quantities are polypropylene battery casings; HDPE, LDPE, LLDPE stretch-wrap and film; PET X-ray films; and polystyrene protective packaging" (p.8)

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[38] This analysis is based upon listings as of January 2005 in the Plastics Directory compiled by the San Francisco Department of the Environment. http://temp.sfgov.org/sfenvironment/directories.plastic/htm
[39] Public presentation by Gabe Wing Miller of Herman Miller, Working Towards a Better World, US Green Building Council, Northern California Chapter, San Francisco, CA, January 18, 2005.
[40] California Integrated Waste Management Board, Plastics White Paper: Optimizing Plastics Use, Recycling and Disposal in California (2003) http://www.ciwmb.ca.gov/Publications/default.asp?pubid=1010

- PVC is a contaminant in plastics recycling: "Contaminants such as other resin grades (especially PVC)" and other materials "require extensive sorting and cleaning" (p.15)
- the recycling rate in California in 2001 for PET bottles was 36%, for HDPE bottles it was 38%, for PP bottles it was 7%, and for PVC bottles it was 1% (pp.32-33)

From the California Integrated Waste Management Board's report emerge the following conclusions. First, the municipal recycling infrastructure in the U.S. is primarily oriented to the recycling of HDPE and PET. Second, the secondary plastics recycled in the U.S. are overwhelmingly from the polyolefin plastics of polyethylenes (HDPE, LLDPE, and LDPE) and polypropylene. Third, PVC is a contaminant, not a valued commodity, in the municipal recycling stream. From these conclusions a crude plastics' recycling hierarchy emerges in the U.S., with PET and HDPE the most recyclable plastics, followed by other polyolefins, and with PVC the most undesirable (see Table 5).

Automotive recycling: The state of plastics recycling in the U.S. mirrors current developments in the automotive sector in Europe and Japan. With legislation requiring the take back of vehicles in Japan and the European Union, automakers are evaluating and selecting for plastics that are more recyclable. Pressed to recycle ever greater percentages of end-of-life vehicles, automakers have completed some of the most extensive assessments on the recyclability of plastic materials.

For example, in 2001, Opel (a European division of General Motors) published its plastics recyclability hierarchy in its environmental report (see Table 4 below). The preferred plastics for recycling were the polyolefins (PP and PE) and the least preferred plastics were a "mixture of incompatible materials" and "PVC."

Table 4. Opel Priority List for Plastics with Regard to Recycling Aspects[41]

Increasing preference → Prefer	
	Polypropylene (PP), Polyethylene (PE)
	Polyoxymethylene (POM), Polyamide, Thermoplastic Urethane (TPU)
	Acrylonitrile Butadiene Styrene (ABS), Polymethylmethacrylate (PMMA, i.e., acrylic), Styrene Maleic Anhydride (SMA) copolymer, Acrylonitrile Styrene Acrylate (ASA), Styrene Acrylonitrile (SAN)
	Polycarbonate, Polyethylene Terephthalate (PET), Polybutylene Terephthalate (PBT)
	Thermoplastic Elastomer (TPE)
	Polyurethane
	Sheet Molding Compound (SMC), Phenol-Formaldehyde (PF)
	Elastomer
	Polyvinyl Chloride (PVC)
	Mixture of incompatible materials

Opel is not alone in its assessment of plastics. Honda, Nissan, and Toyota have all identified polyolefins as the preferred plastics from the perspective of recyclability. Honda, for example, states in its 2003 Environmental Annual Report that it is standardizing for polyolefin resins: "For all of the new models and changed models released in fiscal 2002, highly recyclable olefin resins are now used for injection-molded interior parts"; including trunk decoration, instrument panels, bumper faces, air conditioning units, and door linings.[42] Polypropylene bumpers are now widely recycled in Japan. Nissan, for example, collected 231,576 polypropylene bumpers in 2002 for use as used bumpers (as replacement parts) and with the goal of using the recycled bumpers on new models.[43] Regarding PVC, Toyota in its 2003 Environmental and Social Report stated that it "is actively engaged in reducing the volume of PVC resin used."[44]

[41] Opel. 2001. *Environmental Report 2000/2001*.
[42] Honda. 2003. *Environmental Annual Report 2003*, p.32.
[43] Nissan, 2003. *Environmental and Social Report (year ended March 31, 2003*, pp.32+38.
[44] Toyota. 2003. *Environmental & Social Report 2003*, p.37.

PEX is not referenced in these reports due to its low usage in these sectors. PEX recycling is hampered by the crosslinking of the molecules. Cross-linked plastics like PEX are known as "thermoset" plastics. A thermoset plastic is hardened by curing, creating a three-dimensional, inter-connected structure that cannot be re-melted or re-molded; it is infusible and insoluble.[45] This makes thermosets like PEX very difficult to recycle. The only current recycling option for PEX is to grind it down and use as filler in another material.

Table 5 summarizes the data collected on the recycling and recyclability of the plastics used in pipes. The polyolefins – especially HDPE (municipal bottle recycling) and PP (automotive sector) – are the preferred pipe plastics used in for municipal and automotive recycling programs and with the most acceptance by regional plastic recyclers in the Bay area. ABS is recyclable, but receives little attention in these assessments of plastics recycling because of its smaller levels of production relative to HDPE, PP, and PVC. PEX receives little attention because it is both a relatively small volume plastic and inherently very difficult to recycle.

PVC is a plastic that municipal and automotive recycling programs are actively avoiding. The array of toxic additives included in PVC (as discussed in the previous life cycle section) as well as it being a contaminant in municipal recycling, make it a largely unwanted post-consumer material. While manufacturers of PVC – especially in Europe – are trying to develop a post-consumer recycling market for PVC, their initiative is receiving a lukewarm response from the users of plastics, as exemplified by the automotive sector's decision to de-select PVC.

Table 5. Assessment of Recyclability of Plastics Used in Pipes

	[illegible]		Concern	Prefer	
	PVC	**PEX**	**ABS**	**PP**	**HDPE**
Summary assessment	[illegible]	[illegible]	·Recyclable but small markets	·Established post consumer recycling markets (automotive)	·Established post consumer recycling markets (bottles)
SF area recycling outlets	**5 companies accept drop off**	**None known in bay area**	**7 companies accept drop off, many w/minimum amts**	**11 companies accept drop off**	**13 companies accept drop off**
Municipal bottle recycling	**Contaminant in bottle recycling streams**	**Not applicable, no use in this sector**	**Not applicable - recyclable but little use in this market**	**Marginal levels of recycling**	**Highly recyclable, well established markets**
Automotive recycling	**Among the least preferred plastics**	***No data on PEX use and recycling in this sector***	**Recyclable, moderately preferred, but used in low volumes**	**Highly recyclable, established markets, most preferred**	**Highly recyclable, established markets, most preferred**

[45] Stevens, 2002, p.39. HDPE, PP, ABS, and PVC are all "thermoplastics." Since thermoplastics can be repeatedly softened and hardened by heating and cooling, they are much easier to recycle than thermosets.

Summary of Environmental Preferability Analysis

The hazards and recyclability assessments clearly indicate that PVC is environmentally less preferable than HDPE and PP. ABS and PEX occupy a middle ground between the poles of PVC -- to be avoided -- and HDPE and PP -- to be preferred (see Table 6). ABS is in the middle ground because of its better recycling profile than PVC. For PEX, while it is preferable to ABS and PVC on hazards, questions remain about its recyclability.

- ABS and PVC have more significant Chemicals of Highest Concern across their life cycles than HDPE, PP, and PEX,
    - o PVC is of somewhat greater concern than ABS because of its linkage with chemicals targeted for elimination by international treaty: the Stockholm Convention on POPs
- PVC has a negative recycling profile: it is considered a contaminant in municipal recycling programs.
- ABS and PEX have limited to no recyclability data.
- HDPE through packaging and PP through the automotive sector both have established post-consumer recycling markets.

There are no rating differences between HDPE, PEX and PP in the hazards assessment portion of this analysis. PEX ranks below HDPE and PEX due to its lack of recyclability Therefore HDPE and PP share the highest relative environmental preferability ranking in this assessment, followed by PEX. It is important to keep in mind when reading this analysis that all of these plastics have significant toxicity problems and much of the recycling is still downcycling. There remains much work to be done to find truly environmentally healthy plastics for these applications.

Table 6. Combined Preferability of Pipes based on Hazard and Recycling Assessments

	Avoid	Concern		Prefer	
	PVC	**ABS**	**PEX**	**PP**	**HDPE**
Summary chemical hazard assessment	[illegible]	·EPA PBT & ·EPA/OSPAR Priority outputs plus additional ·Chronic toxicant inputs	·Significant EPA PBT & EPA/OSPAR Priority outputs	·Significant EPA PBT & EPA/OSPAR Priority outputs	·Significant EPA PBT & EPA/OSPAR Priority outputs
Summary recycling markets and recyclability assessment	[illegible]	·Recyclable but small markets	[illegible]	·Established post consumer recycling markets (automotive)	·Established post consumer recycling markets (bottles)

Remember that all of these plastics have significant toxicity problems and much of the recycling is still downcycling. There remains much work to be done to find truly environmentally healthy plastics for these applications.

Performance Evaluation

The final step of this analysis evaluates the performance characteristics for each pipe plastic in different applications. Performance of the different pipe plastics are evaluated for the following applications:

- Water Distribution
- Drain Waste and Vent (DWV)
- Sanitary Sewer
- Storm Sewer
- Irrigation and Drainage

The discussion of characteristics is qualitative where a specific rating measure is not listed. Performance characteristics will be compared across pipe plastics and for their impact on the usefulness of the pipe plastic for each of the applicable applications.

Polyvinyl Chloride (PVC) provides a good combination of long-term strength and high stiffness. PVC has good chemical resistance to a wide range of corrosive fluids, but may be damaged by ketones, aromatic and some chlorinated hydrocarbons. It is used in DWV, storm, sanitary, and water distribution applications.[46] PVC pipe is primarily joined by either by bell and spigot or by chemical solvent cementing - which has additional toxicity problems not addressed in this report.

Acrylonitrile-Butadiene-Styrene (ABS) is formed from three distinct monomer building blocks. Substances of these types are usually referred to as copolymers. The proportions of each substance will determine the physical properties of the final product. In this case, acrylonitrile contributes rigidity, strength, hardness, and chemical and heat resistance. Butadiene contributes impact resistance. Styrene increases the ease of processing. ABS is primarily used for DWV applications. ABS pipe can be joined by solvent welding or threading.[47]

High Density Polyethylene (HDPE) exhibits good chemical resistance, flexibility (without the addition of plasticizers) and abrasion resistance. It can be used for pressure and non-pressure applications and is increasingly available with higher pressure ratings. HDPE retains its strength and flexibility even at subfreezing temperatures. Its inherent flexibility provides better resistance to ground movement, earthquakes, and damage during installation or intrusion during excavations. The flexibility of HDPE has also made it increasingly popular in some parts of the country (including the San Francisco area) for trenchless sewer replacement, providing significant savings in trenching costs and environmental impact. Coiling is possible with small diameter polyethylene pipe which makes it useful for gas distribution and water services. In some applications flexible HDPE pipe can provide cost savings by minimizing and eliminating the need for jointing. The pipe can be bent around corners and around physical obstructions.

The principle joining method is heat fusion, where pipe ends are thermally butt-fused together. This can make a virtually leak-proof joint stronger than the pipe itself and considered by some to be superior to the solvent welds or threaded joints of PVC and ABS. HDPE may also be joined by other methods such as compression fittings.

The primary HDPE applications are: irrigation and drainage, water and storm and sanitary applications[48].

Cross Linked Polyethylene (PEX) is made up of polyethylene molecules that are cross linked in order to raise the maximum operating temperature up to 200 ^{o}F (93 ^{o}C). Other performance characteristics are similar to HDPE. Common applications are primarily inside buildings, including under-floor hydronic heating systems, and hot-cold water systems. PEX pipe is primarily available in small sizes appropriate to these applications. Connections are primarily made with compression fittings.

Polypropylene (PP) shares similar properties with polyethylene and generally has better chemical resistance than other plastics. PP is used in some pressure piping applications, but its primary use is in low pressure lines. Polypropylene plastic pipe is used for chemical (usually acid) waste drainage systems, sanitary and water lines, though almost exclusively outside of North America. In 2004, however, a

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[46] CBD-220. Thermoplastic Pipe, National Research Council of Canada, Institute for Research in Construction http://irc.nrc-cnrc.gc.ca/cbd/cbd220e.html
[47] CBD-220
[48] CBD-220

German firm, Aquatherm, began marketing PP in North America for potable-water, hydronic-heating, and other pressurized piping applications[49]. Another manufacturer intends to introduce a PP sanitary line in 2005[50]. Pipe lengths are joined by heat fusion, threading (i.e., with heavy pipe) and mechanical seal devices.[51]

Pipe Sectors

Within each sector, design, construction and operational and maintenance considerations impact plastic selection. As these sectors differ from one another, it is important to recognize that one plastic may not be appropriate for use over all sectors.

Water Distribution

Water distribution systems are defined as those that convey potable water, typically from water treatment facilities, to the end user. These systems are a tree-like pipe network consisting of:

- Transmission lines - (water mains - typically 36" diameter or less)
- Distribution lines - (lower diameter sizes: 6" - 12")
- Service connections - (from street to building)

Water mains typically operate at pressures from 100 to 150 lbs per sq. in. (psi), while distribution lines operate between 40 and 100 psi[52].

The primary plastics used for water distribution in North America are HDPE and PVC. HDPE pipe performs roughly equivalently to PVC in water main applications, with similar corrosion resistance and durability. HDPE has a slight advantage in terms of preventing leaks as the butt-fusion method used to join HDPE provides stronger, tighter, more leak proof joints compared to the bell and spigot joints used in PVC pipe[53]. PEX is also used in this application, primarily for small diameter distribution applications within buildings. PEX is generally not used for the other applications surveyed here.

Drain, Waste and Vent (DWV)

DWV is essentially the sanitary sewer system before it leaves the property line. PP, PVC, HDPE and ABS are all in use in DWV applications domestically and/or in foreign markets. Because of the wide range of labor, fire and other code issues, selection of DWV can be challenging in North America and one or more of these alternatives has been restricted for DWV use in the USA. For example, New York State labor code prohibits the use of PVC pipe in buildings greater than three stories. Fire codes may prohibit the interior use of HDPE in some states. A full analysis of code restrictions on pipe alternatives in DWV is beyond the scope of this report.

Sanitary Sewer

Sanitary sewers collect wastewater from homes and business and convey it for treatment. Sanitary sewer collection systems, like water distribution systems, are a tree-like pipe network and consist of:

- Interceptor Sewers – (carry wastewater from collecting sewers to the wastewater treatment facility. From 15" up to several feet in diameter)
- Collecting Sewers – (collect from service connections with typical diameters of 6" to 12")
- Service connections – (from street to building).

Sanitary sewers release corrosive gases. Because of the resistance to corrosion provided by the plastics, they are increasingly preferred to non-plastic alternatives for sanitary applications. Currently, PVC is the most widely used plastic for sanitary sewer in North America but HDPE is gaining market share in some areas, including the San Francisco area, particularly for its ability to be used for trenchless sewer replacement (not possible with PVC). HDPE also has a slight advantage in chemical and abrasion

[49] Environmental Building News, "Fusiotherm Polypropylene Piping From Aquatherm", September 2004 Volume 13, Number 9
[50] Personal communication with Jamie Harvie.
[51] CBD-220 NRC
[52] Environment Canada, "A Technical and Socio-Economic Comparison of Options to Products Derived From the Chlor-alkali Industry" 1999
[53] Environment Canada

resistance. On the other hand, gravity lines, such as sewer and drainage require close attention to proper installation gradient to ensure proper flow, whereas pressure lines which do not require this gradient, offer greater leeway. As a result, gravity line pipe is typically installed in sections which allow closer installation and monitoring, which is more difficult with the use of long, more flexible, continuously welded pipe. This has made HDPE more popular for trenchless replacement slip lining than for new sanitary gravity pipe lays, but not exclusively. Hancor, a US pipe manufacturer has just introduced a HDPE pipe, which comes in 20 foot sections and intended for sanitary applications. Available in larger diameters, the pipe is joined through fusion welding.

In Europe, more rigid PP is gaining in popularity. Though it has not yet been marketed for this application in the US, a European manufacturer plans to market a PP pipe for sanitary applications in the US market[54].

Storm Sewer

Prior to the 1960s most sewer systems were combined sewers, that is, carried both sanitary and storm water. The system had to be designed to carry large volumes of water during rain events, but otherwise the capacity was little used. In addition, when it did rain the flood of relatively fresh water often negatively impacted water treatment. Design changed so that by the mid 1960s sanitary and storm systems were designed and constructed separately. Storm sewers collect water from roof drains, parking lots and streets. Unlike sanitary sewers, storm wastewater is not typically treated and the flow is directly discharged into a receiving body of water. PVC and HDPE are the plastics most widely used in North America. Since storm sewers are also a non pressurized, gravity flow application, the performance concerns are similar to sanitary sewer applications, with the notable exception that corrosive gas resistance is less important.

Irrigation and Drainage

PVC, PP and HDPE are all used for irrigation water distribution in the US with similar performance characteristics. Because the distributed water is under pressure, leakage performance is again significant. PVC has dominated irrigation applications in recent years, but HDPE is now beginning to regain share due in part to the labor savings of layout from long coils with fewer joints versus the short rigid sections of PVC and its higher resistance to shovel damage and joint failure.

Plastic pipes, both PVC and HDPE, are gaining rapidly in the huge drainage market previously dominated by concrete and steel. Recently, the Corrugated Polyethylene Pipe Association initiated a third party certification system which allows for increased acceptance of their product by the American Association of State Highway and Transportation Officials. High recycled content HDPE is now available on the market for this application. Performance issues are similar to storm sewer applications.

Duct and Conduit

PVC and HDPE are both used for electrical duct and conduit. Rigid PVC can have an advantage in requiring fewer hangars in suspended applications. Flexible HDPE can have the advantage in easier installation for long continuous runs and bends without requiring joints. HDPE also has a lower coefficient of friction thus making cable fishing and pulling easier. Fire resistant HDPE is available. PP is also used where higher temperature resistance is required, but not widely available in North America.

Cost Issues

All pipe sectors have at least one viable plastic alternative, with the exception in North America of DWV, where there is still limited access to polyolefin based plastic pipes, although Aquatherm's market introduction may change this soon. The issue of cost differential is extremely complex. Conversation with industry officials and literature review suggest that pipe material cost differences, if they do exist, are not the determinant issue in pipe selection[55]. Pipe project costs are highly dependent on a number of important variables which include but are not limited to: market location and its proximity to

[54] Personal communication with Jamie Harvie.
[55] For more discussion on this topic see Harvie, Jamie etal, "PVC-Free Pipe Purchasers' Report", Healthy Building Network 2002, http://www.healthybuilding.net/pvc/pipes_report.html

manufacturing, material/resin costs which can vary rapidly over time, soil and other site conditions, local labor costs, contractor experience with the pipe type, and installation method. While it is difficult to make across the board statements about the cost implications of plastic selection, a recent report found that less toxic alternatives are successfully competing with PVC in many pipe applications.[56]

Lifespan and Durability

There is much debate over the durability and expected lifespan of plastic pipes. The long term durability of piping systems depends on many factors, including the soil environment, proper installation, material properties such as corrosion resistance, chemical resistance and strength and the performance of joints[57]. Because of the characteristics of storm and sanitary flow, conveyance systems must offer good resistance to corrosion, chemicals and abrasion. All plastics under consideration offer good resistance to these forms of degradation. All of the plastics have been on the market for decades[58]. When properly designed and installed, pipe systems of any of these materials can be sufficiently durable to withstand many decades of services[59].

Summary of Performance Evaluation

Table 7 compares the relative performance and availability of the various plastics by application. ABS and PEX have characteristics that lead them to be used primarily in a limited number of applications. PVC, HDPE and PP meanwhile are competitive in most applications with many similar performance characteristics and modest tradeoffs in others. The net result is that plastic alternatives exist in the Prefer category (HDPE and PP) for each of the pipe applications studied that perform equal to or better than the plastics in the Concern or Avoid categories.

Market availability

While regional availability may vary, only the market availability of alternatives for DWV is significantly limited across North America, due in part to state and local building code challenges and part due to manufacturer market decisions. Differences in market share across the applications are primarily a function of the historical marketing focus of the manufacturers rather than of purchaser selection. For example, PVC manufacturers pursued municipal markets before HDPE; hence they have the dominant market share in municipal markets. Meanwhile, HDPE manufacturers targeted industrial markets where HDPE's corrosion resistance created performance advantages.

Access to alternative plastics is growing as manufacturers are increasingly targeting new markets across these traditional boundaries. European PP manufacturers are beginning to enter into the North American market and North American HDPE manufacturers are expanding their offerings to cover more applications. Even in the constrained North American DWV market, options are beginning to emerge. Forward looking environmentally preferable purchasing policies by corporate and government entities can aid this market transformation. There is no reason not to move forward in selection of more preferable alternative pipe plastics.

56 Ackerman, Frank, etal "The Economics of Phasing Out PVC", Tufts University, 2003 http://www.healthybuilding.net/pvc/Economics_Of_Phasing_Out_PVC.pdf

57 Environment Canada

58 PEX has only been in the North American market since 1995 but has been used widely in Europe for decades. Likewise PP has had relatively limited marketing in North America but has been widely used in Europe for decades.

59 Environment Canada

Table 7. Application Specific Performance & Availability Comparison for Plastic Pipes					
	PVC	ABS	PEX	PP	HDPE
- Water distribution	Good/Good	Not used/NA	Good/ Good*	Good/Poor†	Good/Good°
- Drain/Waste/Vent	Good/Good	Good/Good	Not used/NA	Good/Poor†	Not used/NA
- Sanitary sewer	Good/Good	Not used/NA	Not used/NA	Good/Poor†	Good/Good
- Storm sewer	Good/Good	Not used/NA	Not used/NA	Good/None*	Good/Good
- Irrigation & drainage	Good/Good	Not used/NA	Not used/NA	Good/None*	Good/Good
- Duct & Conduit	Good/Good	Not used/NA	Not used/NA	Good/Poor*	Good/Good

First item before the "/" is the general performance assessment. The item after the "/" is the market availability assessment..
Not used means not typically specified or used in these applications. NA means market availability is not applicable as there is no demand because the plastic type is not typically used

* Used only in small diameter pipes, primarily for water distribution and radiant systems in buildings.

° Used primarily in large diameter piping outside the building

† Available in Europe, in early stages of marketing in US in 2005

* Available in Europe, not yet marketed in the US

See Appendix 7 for more detailed charts of plastic pipe performance by application

Conclusion

This study seeks to answer the question of whether there are significant differences between the plastics used to manufacture pipes with a focus on priority environmental health impacts and end of life recyclability. No determination is made on whether plastics are either more or less preferable to the traditional materials used to manufacture pipes. Rather the evaluation is for decision-makers interested in understanding the environmental differences between plastics.

In this report, the plastics used to manufacture pipes are analyzed and compared for chemical hazards, recyclability and performance. The chemical hazard and recyclability assessments evaluate the environmental sustainability of plastics, while the performance assessment gauges the technical, market, and economic viability of the materials in different applications.

Table 8 summarizes the results of the analysis and the conclusions of this report.

The analysis of the existing data leads to four primary conclusions:

- HDPE and PP are the most environmentally preferable plastics currently used to manufacture pipes under this chemical hazard and recyclability based analysis with no significant distinction between them. Yet even these plastics have their environmental downsides.
- HDPE, PP, and PEX create less chemical hazards of high concern across their life cycles than ABS and PVC.
- HDPE and PP are the most recyclable of the materials. There is less of a market for recycling ABS. PEX is not truly closed loop recyclable, and while PVC is marginally recyclable under some circumstances it is considered a contaminant in many recycling programs and increasingly avoided in some sectors.
- Plastic pipe alternatives exist in the Prefer category in this analysis (HDPE and PP) that perform equal to or better than the plastics in the Avoid and Concern categories (PVC, ABS and PEX) for each of the pipe applications studied. Availability of preferable alternatives is good in North American markets with the exception of drain-waste-vent (DWV) applications. The entry of new PP and HDPE products, with encouragement from environmentally preferable purchasing policies, is expected to expand availability of preferable alternative options in the North American market for all applications including DWV.

Table 8. Summary of Plastic Pipe Environmental Preferability Analysis						
	Avoid	Concern		Prefer		
	PVC	ABS	PEX	PP	HDPE	Preferable
Summary of chemical hazard & recyclability assessments	·worst chemical hazard ·poor recyclability	·more chemical hazard ·low recycling	·less chemical hazard ·very limited recyclability	·less chemical hazard ·good recyclability	·less chemical hazard ·good recyclability	Truly preferable plastic pipes do not yet exist
--- Chemical Hazard Assessment ---------						
Stockholm POPs (outputs after refining)	·Dioxins, Furans, Hexachlorobenzene, PCB	+ none	+ none	+ none	+ none	
OSPAR & USEPA PBT & Priority Chemical (inputs)	·Cadmium, Lead, Organotins	+ none	+ none	+ none	+ none	
Chronic toxicants; Carcinogens, mutagens, developmental or reproductive toxicants or endocrine disruptor (inputs)	·Cadmium, Carbon black, EDC, [illegible] compounds, [illegible]	·1,3-butadiene, Acrylonitrile, Benzene, [illegible]	·Carbon black	·Carbon black	·Carbon black	
Other PBT Outputs	[illegible]	[illegible]	[illegible]	·many	·many	
--- Recyclability Assessment---------						
Summary recycling markets and recyclability assessment	·Little recycling; Considered contaminant to municipal recycling	Recyclable but small markets	Very limited; Only recycled as filler in other products; can never be closed loop recycled	+ Established post consumer recycling markets (automotive)	+ Established post consumer recycling markets (bottles)	-
--- Performance / Availability Assessment---------						
- Water distribution	Good/Good	Not used/NA	Good/Good*	Good/Poor*	Good/Good*	
- Drain/Waste/Vent	Good/Good	Good/Good	Not used/NA	Good/Poor	Not used/NA	
- Sanitary sewer	Good/Good	Not used/NA	Not used/NA	Good/Poor	Good/Good	
- Storm sewer	Good/Good	Not used/NA	Not used/NA	Good/None	Good/Good	
- Irrigation & drainage	Good/Good	Not used/NA	Not used/NA	Good/None	Good/Good	

*PEX is used only in small diameter piping primarily for water distribution and radiant systems in buildings. HDPE for water distribution is used primarily in larger diameter piping outside the building. PP is just beginning to be marketed in North America

Appendix 1 - Principles of Decision Making: Life Cycle, Precaution & Pollution Prevention

The screening based method described in this report to evaluate the plastics used in pipes is founded upon three principles:

1) Life Cycle Thinking:

In life cycle thinking the stages of a material's life -- beginning with raw material extraction and ending with disposal (or reuse/recycling/composting) -- provide the frame for evaluating the presence of toxic inputs and toxic outputs. Life cycle thinking, as Todd and Curran (1999) emphasize, is "a unique way [relative to quantitative life cycle assessment (LCA)] of addressing environmental problems from a systems or holistic perspective" because it challenges the "need for a complete inventory of material and energy flows associated with the system of interest."[60] In fact, it challenges not only the need, but also the attainability and the practical usefulness of quantitative LCA in establishing materials policies such as this.

The method used here to evaluate plastic pipes does not attempt to quantify total outputs of toxic chemicals nor normalize results to a functional unit, but rather bases judgments upon screening simply for direct existence or nonexistence of target outputs.

Quantified risk analysis type approaches such as applied by most LCA tools are severely limited in their usefulness for policy judgments for a variety of reasons. Efforts to quantify impacts as they relate to human and ecological toxicity have run up against a number of significant barriers:

- Toxic chemical release data are a poor indicator of potential impacts because there is no simple linear relationship between measured releases and impacts:
    - Some chemicals persist in the environment, bioaccumulate in organisms, and biomagnify up the food chain. The result is that a given amount of release will result in widely different and not readily predictable exposures to different populations dependent upon factors like geography and location on the food chain.
    - Furthermore, many of these same chemicals are toxic at very low doses. Thus small releases of these chemicals – sometimes at levels well below thresholds that are easily monitored for quantification are of high concern. That is, any release – even a very small one - can result in significant exposures in humans and wildlife.
    - Adverse effects may be more a factor of the timing of the exposure -- e.g., the developing fetus exposed to phthalates -- rather than the dose of the exposure.
    - Individuals are exposed to a complex soup of chemicals - many that can cause the same adverse effects and some that are synergistic - rather than only to a single chemical at a time. Thus the cumulative doses of exposure to potential impacts are greater than assumed for any individual chemical. Additional exposures to a single chemical may have threshold or synergistic effects far beyond those predicted by one at a time controlled studies would indicate.
- LCA models suffer from a great paucity of comprehensive and reliably comparable data:
    - Release data is primarily based upon stack and pipe release estimates. Exposures that occur in the workplace, from the use of products, and from food are not included, although they are critically important additive factors to the impact.
    - Release data based upon the Toxics Release Inventory (TRI) database isn't even complete for stack and pipe releases as reporting requirements do not apply to all releasers.
    - Most LCA models are very limited in which datasets are incorporated and may be missing significant portions of life cycle releases.
    - Data are often of widely varying quality across materials and rarely transparent to the user for quality checking.

[60] Todd, Joel Ann and Mary Ann Curran (eds.), 1999, *Streamlined Life-Cycle Assessment: A Final Report from the SETAC North America Streamlined LCA Workgroup* (Pensacola: SETAC).

- The sheer volume of data inputs makes thorough quality checking impossible.
  - The large number of assumptions with high variability and uncertainty generally leads to a high uncertainty in the absolute metric that is rarely reflected in the results of LCAs despite the fact that these uncertainties can be much larger than the differences reflected in the LCA result.
  - Many simplifying assumptions and interpretive algorithms are needed to translate data into common metrics, compare different impact types and pathways and manage the different data sources. These each contain significant assumptions that are seldom transparent to the user.61
- The need to reduce everything to a common metric for LCAs requires reducing every human health impact – including carcinogenicity, mutagenicity, and reproductive, developmental, and neurological toxicity to a relative quantitative value, masking core values.

LCAs have a place in narrowly defined industrial analysis for single manufacturers, where the data set is closely held and the set of parameters to capture is constrained, but for broader materials policy work like this it is sorely lacking. The task of quantification demanded by LCAs is laborious, masks critical values and ultimately at this scale may be of questionable scientific validity.

The method used here based upon life cycle thinking instead uses a more straightforward knock-out screens for the most toxic chemicals of concern. That is, it sets screens for materials based simply upon use of these chemicals or the creation of them as byproducts instead of attempting to compare quantities and scale to assumed impacts.

2) Pollution Prevention:

Reducing toxicants before they are used or generated as byproduct has priority over controlling toxics at the end-of-the-pipe. The primacy of prevention is established in the Pollution Prevention Act of 1990:

> The Congress hereby declares it to be the national policy of the United States that pollution should be prevented or reduced at the source whenever feasible; pollution that cannot be prevented should be recycled in an environmentally safe manner, whenever feasible; pollution that cannot be prevented or recycled should be treated in an environmentally safe manner whenever feasible; and disposal or other release into the environment should be employed only as a last resort and should be conducted in an environmentally safe manner.

When developing a method where prevention has primacy over control, it places the emphasis of the analysis on evaluating whether a toxic chemical is present or absent in the life cycle of a material (just s the life cycle thinking approach does) – as either an input or output in each stage of the material's life cycle – rather than quantifying the amount of the chemical released into the environment for each stage. It is a binary system. Toxic chemicals are either present or not present. A binary system is particularly appropriate when dealing with PBTs, inasmuch as even low level releases can result in significant adverse public and environmental impacts. For example, the International Joint Commission (IJC) concluded in its *Sixth Biennial Report on Great Lakes Water Quality* that "we should immediately begin a process to eliminate" PBTs because "it seems impossible to eliminate discharges of these chemicals through other means." Therefore, continued the IJC, "a policy of banning or sunsetting their manufacture, distribution, storage, use and disposal appears to be the only alternative."[62]

The hierarchy of materials management established in the Pollution Prevention Act also emphasizes the importance of recycling materials before disposing of them. Therefore the method should include an assessment of whether materials are recycled, as well as the impacts that may occur from recycling.

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[61] See *Environmental Building News*, March 2002, "Life-Cycle Assessment for Buildings: Seeking the Holy Grail," Vol. 11, No. 3.
[62] International Joint Commission (IJC), 1992, *Sixth Biennial Report on Great Lakes Water Quality* (Washington, DC: IJC).

3) Precautionary Principle:

Precautionary approach to decision making is especially relevant to the proposed method:

San Francisco's Precautionary Principle Ordinance, passed in 2003, states that it is the responsibility of government agencies to take action to protect human health and the environment in the face of scientific uncertainty[63]. Traditionally governments ask, "How much environmental harm will be allowed?" in San Francisco, decision-makers ask a very different question: "How little harm is possible?"

Taking action on early warnings is incorporated into the screening method by selecting criteria that reflect the presence of materials known to be of concern due to their toxicity, persistence, and bioaccumulative properties. Historically, environmentally harmful activities have only been stopped after they have manifested extreme environmental degradation or exposed people to harm. In the case of PCBs, DDT, lead, and asbestos, for instance, regulatory action took place only after disaster had struck.

Seeking the safer alternatives is a central element of the precautionary approach and involves the careful assessment of available alternatives using the best available science[64]. An alternatives assessment examines a broad range of options in order to present the public with the consequences of each approach. The process takes short-term versus long-term effects or costs into consideration, and evaluates and compares the adverse or potentially adverse effects of each option, giving preference to those options with fewer potential hazards. The screening process used in this plastic pipe assessment presents decision makers with answers to these fundamental questions: "Is this potentially hazardous product necessary?" "What less hazardous options are available?" and "How little damage is possible?"

[63] San Francisco Precautionary Principle Ordinance, Chapter 1 of Environment Code: www.sfenvironment.org
[64] Lowell Statement on Science and the Precautionary Principle (2001).

Appendix 2 - Chemicals Targeted for Elimination / Reduction by the Stockholm Convention, US EPA and OSPAR

CHEMICALS	Stockholm POPs[65]	US EPA PBTs[66]	OSPAR Priority Chemicals[67]	US EPA Priority Chemicals[68]
1,2,4,5-Tetrachlorobenzene				X
1,2,3-trichlorobenzene			X	
1,2,4-trichlorobenzene			X	X
1,3,5-trichlorobenzene			X	
2,4,5-Trichlorophenol				X
2,4,6-tri-tert-butylphenol (phenol)			X	
4-(dimethylbutylamino) diphenylamin (organic nitrogen compound)			X	
4-tert-butyltoluene (aromatic hydrocarbon)			X	
4-Bromophenyl phenyl ether				X
Acenaphthene				X
Acenaphthylene				X
Anthracene				X
Aldrin	X	X		
Benzo(a)pyrene		X		
Benzo(g,h,i)perlyene				X
Brominated flame retardants (BFRs), incl. tetrabromobisphenol A (TBBPA)			X	
Cadmium and compounds			X	X
Chlordane	X	X		
clotrimazole (pharmaceutical)			X	
DDT	X	X		
dicofol (pesticide/biocide)			X	
Dieldrin	X	X		
Endosulfan (pesticide/biocide)			X	X
Endrin	X			
Fluorene				X
Heptachlor	X			X
Hexachlorobenzene	X	X		X
Hexachlorobutadiene				X
Hexachlorocyclohexane isomers (HCH) (pesticide/biocide)			X	X
Hexachloroethane				X
Hexachlorocyclopentadiene (HCCP)			X	
Hexamethyldisiloxane (HMDS) (organosilicane)			X	
Lead and organic lead compounds		X	X	X

[65] The text of the Stockholm Convention can be found at: http://www.pops.int/documents/convtext/convtext_en.pdf
[66] The list of priority PBT chemicals for which the USEPA is developing national action plans can be found at: http://www.epa.gov/opptintr/pbt/
[67] The list of chemicals identified by the OSPAR Commission for priority action can be found at: http://www.ospar.org/eng/html/
[68] The USEPA NPEP list can be found at: http://www.epa.gov/epaoswer/hazwaste/minimize/chemlist.htm

Appendix 2 (continued) - Chemicals Targeted for Elimination / Reduction by the Stockholm Convention, US EPA and OSPAR

Mercury and organic mercury compounds		**X**	**X**	**X**
Methoxychlor (pesticide/biocide)			X	X
Mirex	X	X		
Musk xylene			X	
Naphthalene				X
Neodecanoic acid, ethenyl ester (organic ester)			X	
Nonylphenol/ ethoxylates (NP/NPEs) and related substances (phenol)			X	
Octachlorostyrene (OCS)		X		
octylphenol (phenol)			X	
organic tin compounds			**X**	
Pendimthalin				X
Pentachlorobenzene				X
Pentachloronitrobenzene				X
Pentachlorophenol (PCP) (pesticide/biocide)			**X**	**X**
Perfluorooctanyl sulphonic acid and its salts (PFOS)			X	
Phenanthrene				X
Phthalates: Dibutyl phthalate (DBP), diethylhexyl phthalate (DEHP)			**X**	
Polyaromatic hydrocarbons (PAHs)			**X**	**X**
Polychlorinated biphenyls (PCBs)	**X**	**X**	**X**	**X**
Polychlorinated dibenzodioxins (PCDDs)	**X**	**X**	**X**	**X**
Polychlorinated dibenzofurans (PCDFs)	**X**	**X**	**X**	**X**
Pyrene				X
Short chained chlorinated paraffins (SCCP)			X	
Toxaphene	X	X		
Trifluralin (pesticide/biocide)			X	X
Triphenyl phosphine (organophosphate)			X	
Total # of Chemicals Listed	**12**	**14**	**32**	**31**

Bold rows are chemicals that are evaluated in pipes in this assessment

Appendix 3 - Priority Chemicals of Highest Concern in Outputs

Lifecycle Stages	Stockholm Convention POPs				US EPA PBTs				OSPAR + US EPA Priority Chemicals			
	PVC	ABS	HDPE & PEX	PP	PVC	ABS	HDPE & PEX	PP	PVC	ABS	HDPE & PEX	PP
--- Initial raw material extraction and processing -------							na = not applicable to this plastic		Blank cells = no data collected for this topic			
Brine extraction	No data	na			No data	na			No data	na		
Natural gas / oil extraction	Water effluent: furans				Water effluent: furans, lead and mercury				Water effluent: cadmium, DEHP, furans, lead, mercury, PAHs, pentachlorophenol			
Natural gas processing	none				none				none			
Crude oil refining	Air emissions: dioxins*; Water effluent, raw: aldrin, DDT				Air emissions: dioxins, benzo(a)pyrene; Water effluent, treated: benzo(a)pyrene, lead, mercury; Water effluent, raw: aldrin, DDT				Air emissions: dioxins; Water effluent, treated: cadmium, DBP, PAHs, pentachlorophenol			
Chlorine production	Byproducts: furans, PCBs, hexachlorobenzene	na			Mercury**; Water effluent, treated: lead, Octachlorostyrene	na			Mercury; Water effluent, treated: lead; Water effluent, untreated: cadmium	na		
na = not applicable * from petroleum refining catalyst regeneration **from the mercury cell diaphragm process												
--- Feedstock, Resin, Polymer, and Product Production -------												
Acrylonitrile production	na	No data	na		na	No data	na		na	No data	na	
Benzene production	na	none	na		na	Water effluent, treated: benzo(a)pyrene, lead, mercury	na		na	Water effluent, treated: cadmium, DEHP, lead, mercury, PAHs	na	
1,3 butadiene	na	No data	na		na	No data	na		na	No data	na	

Appendix 3 - Priority Chemicals of Highest Concern in Outputs (continued – 2 of 3)

Lifecycle Stages	Stockholm Convention POPs				US EPA PBTs				OSPAR + US EPA Priority Chemicals			
	PVC	ABS	HDPE & PEX	PP	PVC	ABS	HDPE & PEX	PP	PVC	ABS	HDPE & PEX	PP
--- Feedstock, Resin, Polymer, and Product Production (cont) --------												
Styrene Production	na	none	na		na	Water effluent, treated: benzo(a)pyrene	na		na	Water effluent, treated: PAHs	na	
Ethylene production	none			na	Water effluent, treated: benzo(a)pyrene, mercury			na	Water effluent, treated: DEHP, mercury, PAHs, cadmium			na
Propylene production	na			none	na			Water effluent, treated: benzo(a) pyrene, mercury	na			Water effluent, treated: DEHP, mercury, PAHs, cadmium
Ethylene dichloride (EDC) and vinyl chloride monomer (VCM) production	Byproduct: dioxins, furans, PCBs, hexachlorobenzene	na			Byproduct: dioxins, furans, PCBs	na			Byproduct: dioxins, furans, PCBs, hexachlorobenzene; Water effluent, treated: DEHP, DBP, pentachlorophenol	na		

Appendix 3 - Priority Chemicals of Highest Concern in Outputs (continued - 3 of 3)

Lifecycle Stages	Stockholm Convention POPs				US EPA PBTs				OSPAR + US EPA Priority Chemicals			
	PVC	ABS	HDPE & PEX	PP	PVC	ABS	HDPE & PEX	PP	PVC	ABS	HDPE & PEX	PP
--- Feedstock, Resin, Polymer, and Product Production (cont – polymerization & compounding -------												
ABS poly-merization & compounding	na	No data	na		na	No data	na		na	No data	na	
HDPE poly-merization & compounding	na		none	na	na		none	na	na		Water effluent, treated: PAHs	na
PP poly-merization & com-pounding	na			none	na			none	na			Water effluent, treated: DEHP, PAHs
PVC poly-merization & com-pounding	none	na			none	na			Lead, organotin compounds	na		
--- Product Use -------												
Accidental fires	dioxins / furans ++	none			dioxins / furans	No data			dioxins / furans	No data		
Normal use of Pipe	none				none				organotin or lead com-pounds	No data		
--- End of Life -------												
Landfill disposal	dioxins / furans +	none			dioxins / furans	No data			dioxins / furans	No data		
Incinerator disposal	dioxins / furans++	none			dioxins / furans	No data			dioxins / furans	No data		

na = not applicable to this plastic No data = no data collected for this topic none = none of these chemicals have been measured for this stage of this plastic

+ from landfill fires ++ chlorine is necessary for dioxin formation

Sources: Assessing the impacts of production and disposal of packaging and public policy measures to alter its mix (volume II). Boston: Tellus Institute. 1992
Thornton, Joe, PhD., Pandora's Poison. Cambridge, MIT Press. 2000

Appendix 4 - Average Composition of PVC Sewer Pipes

Inputs	Entec UK Ltd, 2000 (%)	Intron Report #95027 (%)
PVC	92.1	94
Stabilizers		
- tribasic lead sulphate	1.4	
- dibasic lead stearate	0.5	
- lead stearate	0.2	1.1
- lead stearate	0.4	
- lead stailizer		
- tin stabilizer		
Plasticizer		
Filler		3.8
- powdered limestone	4.7	
Stearic acid	0.1	
Synthetic hard wax	0.1	
Paraffin (lubricant)		0.7
Pigment		
- carbon black	0.5	0.2
- titanium dioxide		0.2
Total	100	100
Source: Baitx, Martin, et. al. 2004. Life Cycle Assessment of PVC and of Principal Competing Materials. Brussels: European Commission.		

Appendix 5 - Additives that may be Used with Plastic Pipes

	PVC	ABS	PEX	HDPE	PP
Antioxidants					
		0.1-1.0% by weight of polymer resin		0.15% by weight of polymer resin	0.05-0.25% by weight of polymer resin
		-- Phenolics	-- Phenolics	-- Phenolics	-- Phenolics
	-- Phosphites	-- Phosphites and phosphonites	-- Phosphites	-- Phosphites	-- Phosphites and phosphonites
		-- Thioesters			-- Thioesters
Antistatic agents					
	--	-- Ethoxylated amines	-- Ethoxylated amines	-- Ethoxylated amines	-- Ethoxylated amines
	-- Fatty acid ester		-- Fatty acid ester	-- Fatty acid ester	-- Fatty acid ester
	-- Alkylsufonate	-- Alkylsufonate			
	-- Quaternary ammonium compounds				
Lubricants					
	-- Calcium stearate	-- Zinc stearate	-- Zinc stearates	-- Zinc stearates	-- Zinc stearates
	--	-- Fatty acid amides	-- Fatty acid amides	-- Fatty acid amides	-- Fatty acid amides
	-- Fatty acids and fatty esters		-- Fatty acids	-- Fatty acids	-- Fatty acids
	-- Hydrocarbon waxes: paraffins				
UV light stabilizers					
	-- Carbon black	-- Carbon black	-- Carbon black	-- Carbon black	-- Carbon black
		-- Benzophenones			-- Benzophenones
		-- Hindered amine light stabilizers (HALS)			-- Hindered amine light stabilizers (HALS)
Stabilizers					
	- Lead-based stabilizers	-- na	-- na	-- na	-- na
	-- Organotins				
	-- Cadmium**				
	-- Calcium-zinc				

"na" = not applicable

Sources:
- Modler, Robert, Eric Anderson, and Yosuke Ishikawa. Chemical Economics Handbook, "Plastics Additives," Palo Alto, CA: SRI International. 1997.
- The Plastics Pipe Institute. 1999. Weatherability of Thermoplastic Piping Systems. Washington, DC: The Plastics Pipe Institute.
- Zweifel, Hans (ed.). 2000. Plastics Additives Handbook (5th Edition). Munich: Hanser Publications
- Special Chem database, www.specialchem4polymers.com/resources/search

Appendix 6 - Toxicity of Inputs

Plastics	Chemical Inputs	Carcinogens (multiple lists)	Mutagens (EU CMR List)	Reproductive / Developmental Toxicants (EU CMR List + CA Prop 65)	Endocrine Disruptors (EU Draft List)	Persist-ence (EU List)	Bio-accumulative Capacity (EU List)
ABS	Acrylonitrile	I-2B, N-2, CP65, EU-2					
ABS	Alkylsulfonate (antistatic)	*Need to know the specific chemicals used. But toxicity data are likely to be absent. For example, no toxicity data have been evaluated for "sodium dodecylbenzene sulfonate-iodine complex" (CAS# 53467-01-9) (Pesticides Action Network, "Pesticides Database - Chemicals," 2004).*					
ABS, HDPE, PEX, PP	Fatty acid amides (lubricant)	*Need to know specific chemical. But toxicity data are likely to be absent. For example, no toxicity data have been evaluated for "diethanolamides of the fatty acids of coconut oil" (RTECS, 2003).*					
ABS	Benzene	I-1, N-1, CP65, EU-1		CP65			
ABS, PP	Benzo-phenones	*Need to know the specific chemical used. For example,* bis(dimethyl-amino) benzophenone is a NTP-2 and CP65 carcinogen.					
ABS	Butadiene, 1-3	I-2A, N-1, CP65, EU-1	EU-2	CP65			
PVC	Cadmium (Cd) Compounds	I-1, N-1, CP65, EU-2	EU-2 (selected Cd compounds) [CP65 - Cd, yes; Cd compounds, no]	EU Category 2 (selected Cd compounds)		Metal	
PVC	Chlorine						
ABS, HDPE, PEX, PP, PVC	Carbon Black	I-2B, CP65					
ABS, HDPE, PP	Ethoxylated amine (antistatic)	*Need to know specific chemical. But toxicity data are likely to be absent. For example, no toxicity data have been evaluated for "amines, tallow, ethoxylated, carboxylated" (CAS#: 61791-25-1) (RTECS, 1999).*					
ABS	Ethylbenzene	I-2B					
ABS, HDPE, PEX, PVC	Ethylene						
PVC	Ethylene Dichloride (EDC)	I-2B, N-2, CP65, EU-2					
HDPE, PEX, PP	Fatty acids and esters (antistatic + lubricant)	*Need to know specific chemical. But toxicity data are likely to be absent. For example, no toxicity data have been evaluated for "fatty acids, coconut oil, sulfoethyl esters, sodium salts" (CAS# 61789-32-0) (RTECS, 1997).*					
ABS, PP	Hindered amine light stabilizers (HALS)	*The US EPA, TSCA New Chemicals Program, concluded in 2001 that the category "Hindered Amines" is "at present not well defined." Health concerns for the category, according to the EPA are based on data submitted for Tinuvin 144 and Chimassorb 944: "The data indicate that these hindered amines, and presumably hindered amines similar in structure, are toxic to the immune system, liver, blood, the male reproductive system, and the G.I. tract" (US EPA, 2001). However, HALS are not listed by either the EU or Prop 65 as reproductive/developmental toxicants.*					
PVC	Lead Compounds	I-2B, CP65		EU-1 (selected lead compounds); [CP65 - lead, only no compounds		Metal	

Plastics	Chemical Inputs	Carcinogens (multiple lists)	Mutagens (EU CMR List)	Reproductive / Developmental Toxicants (EU CMR List + CA Prop 65)	Endocrine Disruptors (EU Draft List)	Persist-ence (EU List)	Bio-accumulative Capacity (EU List)
PVC	Organotins				EU-1	Metal	
PVC	Paraffin (lubricant)	*Limited carcinogenicity studies have been done on paraffin (CAS# 8002-74-2) fumes, but none of the lists assessed here include paraffin as a carcinogen.*					
ABS, HDPE, PEX, PP	Phenolics (antioxidant)	*Need to know the specific chemical used. For example Bisphenol A (CAS #: 80-05-7) is a Category 1 endocrine disruptor in the EU.*					
ABS, HDPE, PEX, PP	Phosphites (antioxidant)	*Need to know specific chemical. But toxicity data are likely to be absent. For example, no chronic toxicity data are available for "bis(2-ethylhexyl) phosphite" (CAS#: 3658-48-8) (RTECS, 1997).*					
PP	Propylene						
PVC	Quaternary ammonium compounds	*No chronic toxicity data available (RTECS, 2003), yet there is evidence that these compounds can cause occupational asthma (Purohit, et al., 2000)*					
ABS	Styrene Monomer	I-2B			EU-1		
ABS, PP	Thioesters (antioxidants)	*Need to know specific chemical. But toxicity data likely to be absent. E.g., no chronic toxicity data available for "methyl demeton thioester" (CAS#: 919-86-8) (RTECS, 1997).*					
PVC	Vinyl Chloride Monomer(VCM)	I-1, N-1, CP65, EU-1					
ABS, HDPE, PEX, PP	Zinc stearate (lubricant)						

"Blank cells" = no data found for that endpoint

Carcinogen abbreviations

"I": International Agency for Research on Cancer (World Health Organization)
- I-1: Carcinogenic to humans
- 2A: Probably carcinogenic to humans
- 2B: Possibly carcinogenic to humans

"N": National Toxicology Program (Health and Human Services Dept., Public Health Service, NIH/NIEHS
- 1: Known to be carcinogenic
- 2: Reasonably anticipated to be carcinogens

"CP65": California Proposition 65 - Chemicals Known to the State to Cause Cancer

"EU": European Union Consolidated List of C/M/R Substances
- 1: Category 1
- 2: Category 2

Mutagens

"EU CMR List": European Union Consolidated List of C/M/R [Carcinogen/Mutagen/Reproductive toxicant] Substances"

Reproductive / Developmental Toxicants

"EU CMR List": European Union Consolidated List of C/M/R Substances"

"CP65": California Proposition 65 - Chemicals known to the state to be developmental / reproductive toxicants

Endocrine Disruptors

European Union (EU) "Candidate List of Substances" (2000)
- "EU-1": Category 1: At least one study providing evidence of endocrine disruption
- "EU-2": Category 2: Potential for endocrine disruption

Persistence & Bioaccumulative Capacity

Swedish National Chemicals Inspectorate (Keml)

Appendix 7 - Performance Comparison of Pipe Plastics

Comparative Technical Data for the Pipe Plastics [69]								
Type of Plastic	Density, g/cm³ (ASTM D 792)	Coefficient of Thermal Expansion, 10^{-6}/°C (ASTM D 696)	Tensile Strength, (psi) (ASTM D 638)	Compressive Strength, (psi) (ASTM D 695)	Temperature Limits (F) Pressure applications	Temperature Limits (F) Non pressure applications	Flexural Strength, (psi) (ASTM D 790)	Modulus of Elasticity, (10^5-psi) (ASTM D 638)
PVC	1.38	50	7,000	9,600	158	179 (210 CPVC)	14,500	4.5
HDPE	0.95	130	2,800	3600	140	194	2,000	0.20
ABS	1.04	101	5,500	7,700	158	176	10,000	3.1
PEX[70]	0.95	141	3,900		210	210[71]	15,000	1.5
PP	0.91	68	4,900	8,500	180	194	8,500	1.5

The following tables provide an overview of important design and operational considerations for the plastics in various pipe sectors:

Water and Pressure Sanitary					
	PVC	ABS*	PEX	HDPE	PP**
Durability	G	N/A	G	G	G
Joint integrity	G	N/A	E	E	E
Pressure rating		N/A	G	G	G
Abrasion resistance	G	N/A	E	E	E
Chemical resistance	G	N/A	No data	E	E

*ABS is not generally used for pressure applications.
** PP is widely available in Europe, but just beginning to be marketed in North America.

DWV					
	PVC	ABS	PEX*	HDPE**	PP**
Durability	G	G	N/A	G	G
Joint integrity	G	G	N/A	E	E
Pressure rating	G	P	N/A	G	G
Abrasion resistance	G	No data	N/A	E	No data
Chemical resistance	G	G	N/A	E	E

* The flexibility and other considerations preclude the use of PEX for use in this sector.
**HDPE is not generally used for this application. PP is just beginning to be marketed in North America

[69] [69] National Resource Council of Canada website http://irc.nrc-cnrc.gc.ca/cbd/cbd220e.html
[69] http://www.vanguard.ca/products/canplumb.pdf
[69] Suggested Temperature Limits for the Operation and Installation of Thermoplastic Piping in Non-Pressure Applications TN-11/99 http://www.plasticpipe.org/pdf/pubs/notes/TN11-99.PDF
[70] Vanguard pipes http://www.vanguard.ca/products/canplumb.pdf
[71] Suggested Temperature Limits for the Operation and Installation of Thermoplastic Piping in Non-Pressure Applications TN-11/99 http://www.plasticpipe.org/pdf/pubs/notes/TN11-99.PDF

Sanitary Sewer (Gravity)					
	PVC	ABS	PEX*	HDPE	PP**
Durability	G	G	N/A	G	G
Joint integrity	G	G	N/A	G	G
Pressure rating	G	P	N/A	G	G
Abrasion resistance	G	No data	N/A	E	E
Chemical resistance	G	G	N/A	E	E

* The flexibility and other considerations preclude the use of PEX for Sanitary Sewer.
** PP sanitary pipe is widely available in Europe but just beginning to be marketed in North America

Storm Sewer					
	PVC	ABS*	PEX**	HDPE	PP***
Durability	G	N/A	N/A	G	G
Joint integrity	G	N/A	N/A	E	E
Pressure rating	G	N/A	N/A	G	G
Abrasion resistance	G	N/A	N/A	E	E
Chemical resistance	G	N/A	N/A	E	E

*ABS is not generally available for Storm Sewer Applications. T
** The flexibility and other considerations preclude the use of PEX for Storm Sewer.
*** PP is generally not marketed for storm sewer applications.

Irrigation and Drainage					
	PVC	ABS **	PEX*	HDPE	PP***
Durability	G	G	N/A	G	G
Joint integrity	G	G	N/A	E	E
Pressure rating	G	P	N/A	G	G
Abrasion resistance	G	No data	N/A	E	No data
Chemical resistance	G	G	N/A	E	E

* The flexibility and other considerations preclude the use of PEX for use in this sector.
**ABS is generally not used for irrigation and drainage applications
*** While PP is frequently used for fittings in this market it is not typically used for irrigation or drainage pipes

As these tables demonstrate, ABS and PEX have particular niche markets and the rest of the plastics are competitive across applications from a performance perspective.

References for rankings in tables:

- Chemical resistance: http://irc.nrc-cnrc.gc.ca/cbd/cbd220e.html reference for
- Abrasion and chemical resistance http://www.cheresources.com/plpipezz.shtml
- Joint integrity and durability and chemical resistance and abrasion http://www.on.ec.gc.ca/water/greatlakes/data/chlor-alkali

Appendix 8 - Glossary of Abbreviations

ABS	Acrylonitrile-butadiene-styrene
ASTM	American Society for Testing and Materials
Cd	Cadmium
CMR	Carcinogen, mutagen or reproductive toxicant
CPVC	Crosslinked polyvinyl chloride
DBP	Dibutyl phthalate
DEHP	Di(2-ethylhexyl) phthalate
DWV	Drain-waste and vent
EDC	Ethylene dichloride
EU	European Union
HDPE	High density polyethylene
Hg	Mercury
IARC	International Agency for Research on Cancer
LCA	Life Cycle Assessment
LDPE	Low density polyethylene
LLDPE	Linear low density polyethylene
OSPAR	Oslo-Paris Convention for the Protection of the Marine Environment of the North East Atlantic
PAH	Polyaromatic hydrocarbon
Pb	Lead
PBT	Persistent Bioaccumulative Toxic
PCB	Polychlorinated biphenyls
PCP	Pentachloro-phenol
PET or PETE	Polyethylene terephthalate
PEX	Cross linked polyethylene
POP	Persistent organic pollutant
PP	Polypropylene
PVC	Polyvinyl chloride
Stockholm	Stockholm Convention on Persistent Organic Pollutants
TRI	Toxic Release Inventory (US EPA)
USEPA	United States Environmental Protection Agency
UV	Ultraviolet
VCM	vinyl chloride monomer

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